METHODS OF MEASUREMENT OF DIELECTRIC CHARACTERISTICS AT COMMERCIAL FREQUENCIES

By

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DISSERTATION

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VITA

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THE TRANSFORMER BRIDGE

By J. B. McCurley,[1] W. B. Kouwenhoven[2] and P. H. Dike[3]

The Schering bridge has long been recognized for its accuracy and dependability in the measurement of the dielectric characteristics of insulating materials. Its successful operation requires considerable care and skill in manipulation, and for accurate work a carefully designed shield and guard system is necessary. This demands a double balance of the bridge by successive approximations, which makes the operation slow in routine testing.

To meet these objections a bridge for the measurement of dielectric characteristics at commercial frequencies has been devised and is described in this paper. This bridge is a Leeds & Northrup modification of the Doyle and Salter[4] transformer bridge, and has for its distinguishing features, rapidity and ease of operation, and a simple shielding arrangement which eliminates the complex guard balancing circuits.

The transformer bridge is not intended for use where the ultimate in accuracy and precision is required. It provides, however, an exceedingly simple and conveniently operated method which is at the same time reasonably accurate. The experimental bridge with 1000 volts applied to the specimen gave results which were accurate and reproducible to ± 0.00003 in power factor on specimens of known characteristics.

General Description

The transformer bridge is shown in Fig. 1. A high-voltage transformer T_1, one end of which is grounded, supplies power for the standard C_s and the specimen C_x. A low-voltage transformer T_{3-4}, having a center tapped secondary with the center tap connected to ground, feeds the auxiliary arm consisting of a resistor R_4 and the balancing arm composed of a resistor R_3 in shunt with a mica capacitor C_3. Resistors R_3 and R_4 and capacitor C_3 are variable. The standard capacitor C_s is preferably a variable air capacitor with a negligible phase angle, though a fixed capacitor having a known phase angle may be used.

The detector is connected between ground and the common junction of R_3, C_3, and R_4 marked A in Fig. 1. A double pole, double throw switch

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[4] E. D. Doyle and E. H. Salter, "Methods of Measuring Dielectric Power Loss and Power Factor," *Transactions*, Am. Inst. Electrical Engrs., Vol. XLV, p. 630 (1926).

not shown in the figure is used to interchange the standard and specimen; that is, to change the circuit from that shown in "Position A" to the one shown in "Position B" of Fig. 1. A study of this figure will show that C_x in position A and C_s in position B act simply as a load on transformer T_1. Their currents do not enter the galvanometer circuit; hence, the only influence they can have on the balance relation is by changing the voltage E_2 due to the regulation of T_1. Interchanging C_x and C_s, as mentioned above, keeps the load constant on transformer T_1 since in either position T_1 supplies both C_s and C_x. Therefore E_2 remains constant.

As shown and as used, a coupling transformer connects the bridge to the amplifier. If one side of the amplifier is connected to ground the

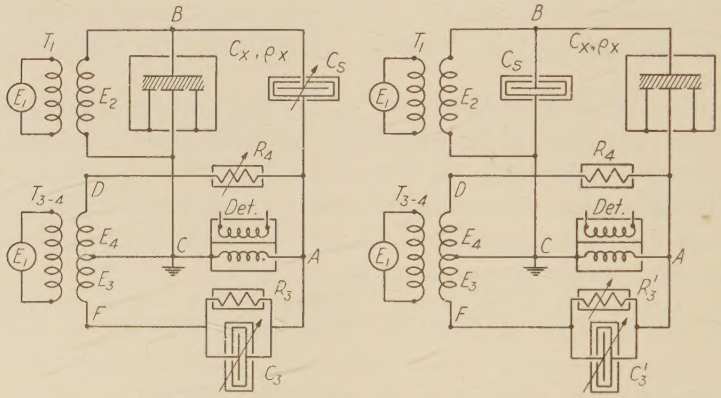

FIG. 1.—The Transformer Bridge.

coupling transformer may be dispensed with. This is a highly commendable feature since such a transformer may introduce both electrostatic and electromagnetic troubles which are sometimes extremely difficult to cope with.

The flexibility of this bridge may be considerably increased by the insertion of a variable voltage transformer such as the Variac[1] to feed the primary of T_{3-4}. The reason for this will be discussed later. Briefly, it is used to control the magnitude of the voltages E_3 and E_4. If the Variac or some other device for varying the primary potential of T_{3-4} is not used both T_1 and T_{3-4} are fed directly from the same source, that is, they are both energized by E_1 as shown in Fig. 1.

The phase angle that exists between the voltage E_2 and the voltage $E_3 + E_4$ does not affect the results provided good transformers are used.

[1] "The Variac—A New Adjustable Transformer," *The General Radio Experimenter*, Vol. VIII, Nos. 1 and 2, p. 5 (1933).

The bridge may be looked upon as made up of four main arms and an auxiliary circuit. The four arms are: (1) the secondary of transformer T_1; (2) C_s or C_x; (3) the lower half of the secondary of transformer T_{3-4}; and (4) R_3 and C_3 in parallel. The auxiliary circuit is made up of the other half of the secondary of transformer T_{3-4} and the resistor R_4 which serves to balance the conductance of the R_3, C_3 arm when C_s is in the circuit and part of this conductance when C_x is in the circuit.

All elements are shielded and all shields are tied to ground. If the standard and specimen have guards they may also be connected directly to ground, thus eliminating the necessity of elaborate guard balancing circuits.

OPERATION

There are a number of methods of operating the transformer bridge. These methods may be divided into two classifications: (1) operation with a variable standard C_s and (2) when equipment is limited operation with a fixed standard C_s and a fixed resistor R_4. In both classes there are two different methods of balancing. They are:

(*a*) Balance made with C_3, R_3, and R_4

(*b*) Balance made with C_3 and R_3 with R_4 fixed.

The operating procedure will now be given for these two methods.

Method 1 (a) C_s Variable, Balance Made with C_3, R_3, and R_4:

The method of operation is as follows:

With the elements arranged as shown in Fig. 1, position B, set R_3 at 10,000 ohms, or some other convenient value, and obtain a balance by adjusting C_3 and R_4.

Let their values be C_3' and R_4', respectively.

Switch to position A and rebalance with C_s and R_4 and let their values be C_s and R_4 respectively. During this operation R_3 and C_3 are not disturbed, that is, they still have values 10,000 ohms and C_3'.

Switch to position B and rebalance by changing R_3 to R_3'.

The constants of the unknown capacitor C_x are then given by the following equations:

$$C_x = C_s \qquad (1)$$

$$\delta_x = \frac{R_3 - R_3'}{\omega C_3' R_3' R_3} \qquad (2)$$

where δ_x = specimen power factor, and

$$\delta_x = \frac{10{,}000 - R_3'}{10{,}000\ \omega C_3' R_3'}, \text{ if } R_3 \text{ is set at 10,000 ohms as suggested above} \qquad (3)$$

These equations and all others used in this paper have been derived mathematically and their accuracy proven by experimental results. The mathematical analysis is entirely too long to be given in a paper of this

nature where the average reader is not particularly concerned with the mathematical aspects but rather the field of application and utility of the bridge. A complete analysis may be found in the unabridged dissertation of McCurley.[1]

Method 2 (a), C_s Fixed, Balance Made with C_3, R_3, and R_4:

To operate, arrange elements as shown in Fig. 1, position A. Set $R_3 = 10{,}000$ ohms and balance the bridge by means of R_4 and C_3.

Switch to position B. Do not disturb R_4 and balance with C_3 and R_3. Let their new values be C_3' and R_3'.

Then

$$C_x = C_s \frac{C_3'}{C_3} \quad (4)$$

and

$$\delta_x = \frac{1}{\omega C_3'}\left(\frac{1}{R_3'} - \frac{K}{R_4}\right) - \frac{1}{\omega C_3}\left(\frac{1}{R_3} - \frac{K}{R_4}\right) \quad (5)$$

where $K = \dfrac{E_4}{E_3}$ the ratio of voltages across the points CD and CF respectively.

Method 1 (b), C_s Variable, R_4 Fixed, Balance Made with C_3 and R_3:

To operate, with elements arranged as shown in Fig. 1, position B, balance the bridge by means of R_3' and C_3'.

Shift to position A and rebalance by means of C_s and R_3, that is, change R_3' to R_3; leave C_3' undisturbed.

Under these conditions Eqs. 1 and 2 hold.

Method 2 (b), C_s and R_4 Fixed, Balance Made with C_3 and R_3:

To operate, arrange elements as shown in Fig. 1, position A, and balance bridge by means of R_3 and C_3.

Shift to position B and balance by changing R_3 to R_3' and C_3 to C_3'.

The balance equations for this method are Eqs. 4 and 5.

SHIELDING ARRANGEMENT

All the elements of the bridge are inclosed in grounded shields which eliminate entirely inter-element capacitances. The presence of these shields introduces capacitance to ground which act simply as loads on their respective transformers, as may be seen from a study of Fig. 1.

The specimen is provided with a guard electrode which is connected directly to ground. At balance the measuring electrode is also at ground potential and thus the necessity of an elaborate guard balancing circuit is entirely eliminated.

[1] J. B. McCurley, "Methods of Measurement of Dielectric Characteristics at Commercial Frequencies," A Dissertation, Johns Hopkins University (1934).

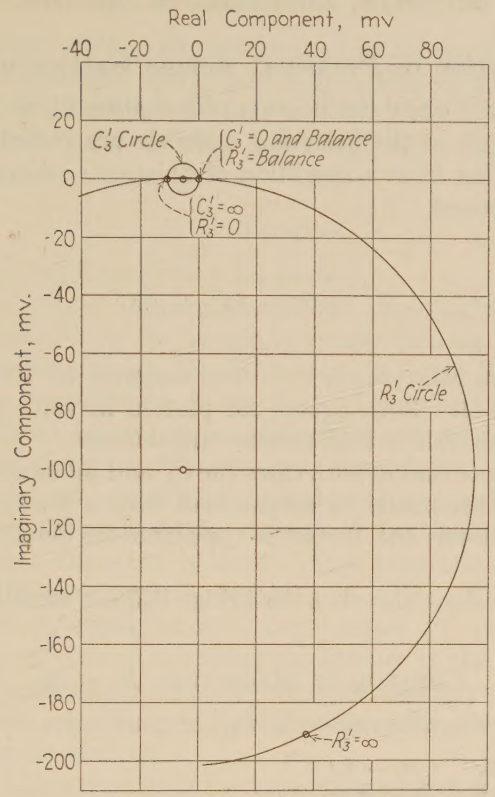

FIG. 2.—Variation of Galvanometer Potential $m = 100$.

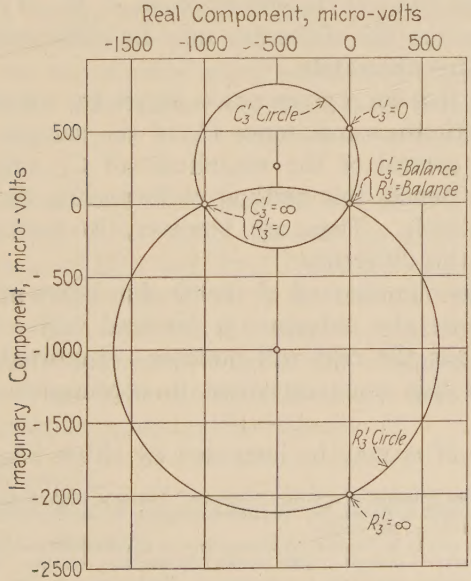

FIG. 3.—Variation of Galvanometer Potential $m = 1000$.

VARIATION OF POTENTIAL ACROSS GALVANOMETER

Figures 2 and 3 show the manner of variation of the potential across the detecting circuit as the balancing elements are varied over their complete range, starting from a condition of balance. Seletzky's[1] method of analysis was employed.

In both cases:

$$\delta_x = 0.01$$
$$\omega C_x = 50 \times 10^{-9} \qquad (C_x = 132. + \mu\mu f.)$$
$$R_4 = 10^4$$

In Fig. 2 the ratio $E_2/E_3 = m$ was assumed as 100. The ratio m was 1000 for Fig. 3. Both figures are plotted in volts across the galvanometer circuit per volt of high-tension transformer.

One should note that in both cases the C_3' and R_3' circles are orthogonal, hence, an a.c. galvanometer in conjunction with a phase shifter, such as used by Kouwenhoven and Banos[2] is applicable for detecting unbalance in this bridge.

These circles show also that the bridge is quite sensitive to changes in resistance.

CONTROL OF MAGNITUDE $R_3 - R_3'$

Since $C_3' = mC_x$ where $m = E_2/E_3$, one may write

$$\delta_x = \frac{R_3 - R_3'}{\omega C_3' R_3' R_3} = \frac{R_3 - R_3'}{m\omega C_x R_3' R_3}$$

The numerator involves the difference, $R_3 - R_3'$, of two large numbers. For low power factors this difference may be quite small and, therefore, difficult to determine accurately.

One will note that for a given power factor the magnitude of $R_3 - R_3'$ varies directly with the capacitance C_x of the sample. One is usually restricted in the control of the magnitude of C_x and frequently C_x is definitely fixed. Hence, this method of increasing the difference is not particularly practicable. There are, however, two methods for controlling the magnitude of this difference:

1. Use 100,000 ohm instead of 10,000 ohm boxes in R_3 and R_4. This scheme will increase the difference a hundred fold. However, for the same quality of box the cost will increase. Kouwenhoven and Marks[3] have pointed out this same expedient in conjunction with the parallel resistance bridge.

2. The value of m may be increased by either lowering the value of

[1] A. C. Seletzky, "Cross Potential of a 4-Arm Network," *Electrical Engineering*, December, 1933, p. 861.
[2] W. B. Kouwenhoven and A. Banos, Jr., "A High Sensitivity Power Factor Bridge," *Transactions*, Am. Inst. Electrical Engrs., Vol. 51, p. 202 (1932).
[3] W. B. Kouwenhoven and L. W. Marks, "A Comparison of the Methods for Testing Insulating Materials for Power Factor and Dielectric Constant at 1000 Cycles," *Proceedings*, Am. Soc. Testing Mats., Vol. 34, Part II, p. 821 (1934).

E_3 or increasing that of E_2. The former may be accomplished by means of a Variac or other potential controlling device, thus considerably increasing the flexibility of this bridge. Figures 2 and 3 show how a change in m influences the importance of R_3'. One will note that for $m = 1000$, $R_3 - R_3'$ is ten times as large as for $m = 100$.

EXPERIMENTAL

Effect of Shielding and Transformer Regulation:

It was stated under the section entitled shielding that any effective capacitance introduced by the shields is always directly across one of the three transformer secondaries, that is, across E_2, E_3, or E_4, and constitutes simply a load on transformers T_1 or T_{3-4}. To prove that such loads as would be introduced by any reasonable shielding arrangement have an entirely negligible effect, the following tests were made:

1. The bridge was carefully balanced with a sample in the circuit. A load of 1 μf., consisting of a mica capacitor, was then thrown across CF, Fig. 1, and did not upset the balance. This same load was then placed across CD with the same negative results.

2. A variable air capacitor was placed across BC and a load of 1300 $\mu\mu$f. was introduced without upsetting the balance in the least.

From these results one may safely conclude that any shielding arrangement within reason and likely to be encountered in practice will have no effect on the balance relations.

These results also show that for capacitance changes the regulation of the transformers used was not such as to cause an upset in the balance. As a further check on T_{3-4} a variable resistor was placed across CF and it was found that this resistance could be lowered, without causing unbalance, to 4000 ohms for one transformer which we shall call A and 1500 ohms for another designated B. The resistor was then placed across CD and lowered to 3000 ohms for transformer A and 1000 ohms for transformer B without an upset in balance.

Now these burdens were in all cases far in excess of any contemplated in practice. Thus from these results one may conclude that for all power factors the regulations of the transformers may be neglected for samples of less than 1000 $\mu\mu$f. if the ratio of E_2 to E_3 is 1000. The reason for this statement lies in the fact that for this ratio a C_x of 1000 $\mu\mu$f. makes C_3 equal to 1 μf. Since it may seem to some that a sample of this size might cause an upset in T_1 let us recall the fact that a load of 1300 $\mu\mu$f. was thrown across E_2 without upsetting the balance.

Check of Balance Relations:

To check the validity of Eq. 2 the power factor standard of Kouwenhoven and Berberich[1] was used.

[1] W. B. Kouwenhoven and L. J. Berberich, "A Standard of Low Power Factor," *Transactions*, Am. Inst. Electrical Engrs., Vol. 52, p. 521 (1933).

The following results were obtained:

$C_3 = C_3' = 0.522 \times 10^{-6}$ farads $\qquad R_3 = 10{,}000$ ohms
$R_3' = 9961.3$ ohms and $R_4 = 10{,}060$ ohms

From these values δ_x was calculated and found to be 0.001974 which compares favorably with the power factor of the standard, namely, 0.00199. The apparent error was less than 1 per cent.

Since R_3' could only be adjusted to within about 0.5 or 0.6 ohm with accuracy, this corresponds to a sensitivity of about ± 0.00003 in power factor. Hence, the above apparent error may be attributed to this cause.

As a further check the Variac was changed three days later and the following results obtained:

$C_3 = C_3' = 0.5747 \times 10^{-6}$ farads $\qquad R_3 = 10{,}000$ ohms
$R_3' = 9957.7$ ohms

This gives a power factor $\delta_x = 0.001965$ which again checks within the limit of sensitivity. The apparent error was 1.4 per cent.

For the next smaller value of the power factor standard, that is, 0.000996 the balance values were $C_3 = C_3' = 0.5747$ μf., $R_3 = 10{,}000$ ohms and $R_3' = 9979.6$ ohms from which the power factor $\delta_x = 0.000945$ or an apparent error of 5.1 per cent. It is not remarkable that this error is considerably larger than those obtained for the larger values of the power factor standard since the numerator of the expression for δ_x involves the term $R_3 - R_3'$ which in this case is only 20.4 ohms and a cumulative error in obtaining R_3 and R_3' amounting to 1 ohm will cause an error of 5 per cent for this low power factor.

As a check on the validity of the relation $\frac{C_x}{C_s} = \frac{C_3'}{C_3}$ given in Eq. 4, the standard was set at some convenient value and C_3 read; C_3 was then changed to C_3', and a new balance obtained by changing C_s to a new value C_x with the following results:

C_s	C_3	C_3'	C_x CALCULATED	C_x MEASURED
150 μμf.	0.1616 μf.	0.1305 μf.	121 μμf.	123 μμf.
154 μμf.	0.1636 μf.	0.1643 μf.	155 μμf.	154 μμf.
191 μμf.	0.2046 μf.	0.1744 μf.	163 μμf.	163 μμf.
240 μμf.	0.2590 μf.	0.2749 μf.	255 μμf.	254 μμf.
300 μμf.	0.3257 μf.	0.3128 μf.	288 μμf.	288 μμf.

In the above, C_x calculated was determined from Eq. 4 and C_x measured was the value obtained from the calibration chart of the standard C_s. Each scale division on C_s was equal to 6 μμf. and if we assume that the scale could be read accurately to a quarter of a division this would represent 1.5 μμf. All the readings given above fall within this tolerance with the exception of the first, but since this is only 0.5 μμf. greater than the tolerance expected one may safely conclude that the relation $C_x = \frac{C_s C_3'}{C_3}$ is correct.

As a check on Eq. 5 and to show that the various methods of operation give consistent results three samples having a wide range in power factor were measured with the following results:

Sample	Capacitance, $\mu\mu$f.	Method 1 (*a*)	Method 1 (*b*)	Method 2 (*a*)	Method 2 (*b*)	Mean Value	Maximum Deviation from Mean Value, per cent
No. 1.....	155	0.0517	0.0516	0.0517	0.0515	0.0516	0.194
No. 2.....	163	0.1760	0.1755	0.1755	0.1750	0.1755	0.285
No. 3.....	254	0.3220	0.3215	0.3212	0.3215	0.3216	0.124

The dielectric in sample No. 1 was paper laminated, in sample No. 2 was clear yellow bakelite, and in sample No. 3 was black bakelite, all commercial insulating materials.

In all cases samples were kept at constant temperature and humidity for at least 12 hours prior to taking readings. In Eq. 5, K was determined by means of a quadrant electrometer.

The power factor sensitivity used in the above was approximately 0.0005. This allowed an extremely quick and easily made balance such as the bridge is intended for.

Sensitivity and Accuracy

The degree to which the difference $R_3 - R_3'$ may be determined is the factor which controls both the sensitivity and accuracy of this bridge.

The sensitivity of the bridge as measured by calculating the power factor corresponding to the minimum positively detectable upset in R_3 was 0.00003. To obtain this sensitivity with the set-up used required careful adjustment of the bridge. The results obtained with the power factor standard show clearly that this sensitivity was realized.

These results show the sensitivity and accuracy that may be expected with careful operation. However, the bridge is intended to give a quick and easily operated method for the determination of the power factor of specimens such as sheet dielectrics. Operated in this manner the sensitivity will naturally be somewhat less.

Reproducibility of Results

The reproducibility of results and hence the reliability of the bridge may be shown by the fact that for about two months one sample showed the same value of measured power factor, 0.00284, to within the sensitivity used which was 0.00003. The sample was kept at a temperature of 25.1 C. and at a relative humidity of 62.5 per cent.

No change could be detected in the difference $R_3 - R_3'$ but during this time there was a change in C_3' of 0.01 per cent which is entirely negligible so far as its effect on power factor is concerned.

SUMMARY

The transformer bridge offers to a user a rapid and at the same time reasonably accurate method for the determination of dielectric characteristics. No guard balancing circuit is necessary and the shielding arrangement offers no difficulties. With fairly good equipment, phase angles in the elements, with the exception of the standard C_s, have a negligible influence on the balance relations. Two methods of controlling the magnitude of the difference $R_3 - R_3'$ have been pointed out.

The sensitivity and therefore the accuracy of the bridge was 0.00003 for power factor if operated carefully. Extremely rapid measurements could be made if an accuracy in power factor of only ± 0.0005 was desired. There are a number of methods of operation available.

The preferred method of operation is method 1 (*a*) for in this all correction terms are eliminated and the calculations are the least involved. One pays for this advantage by the necessity of an additional balance and by the requirement of an adjustable standard capacitor. However, since a knowledge of K and the correct value of R_4, as is the case in Method 2 (*a*), are no longer required these sources of error vanish.

Methods 1 (*b*) and 2 (*b*) are almost as good as the above provided a balance can be obtained with the value of R_1 used. The outstanding advantages of the preferred method are: greater ease of calculation and possibility of balancing with a variable, R_1, whereas it might be impossible to balance with R_4 fixed.

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A MODIFIED SCHERING BRIDGE

By W. B. Kouwenhoven,[1] P. H. Dike,[2] and J. B. McCurley[3]

Synopsis

This paper describes a modified form of Schering bridge, completely shielded and guarded, which was developed by the Leeds & Northrup Co. and studied and improved in a joint investigation carried on by that company and the Electrical Laboratories of The Johns Hopkins University. This bridge possesses several novel features including a new method for balancing or compensating for the residual capacitance of the variable capacitor arm. It also uses a low voltage low impedance scheme for adjusting the shields and guards to the proper potential. The method of operation is discussed, the mathematical treatment is outlined, and certain experimental results are also given in this paper.

In Schering's[4] original bridge, Fig. 1, in which he recommended that R_3 be set to some convenient value and that R_4 and C_3 be varied to obtain balance, the power factor, δ_x, of the specimen C_x, is given by the expression:

$$\delta_x = \omega C_3 R_3$$

From this equation it is evident that the smallest power factor which can be measured with this arrangement is limited by the minimum or residual capacitance of C_3, provided ω and R_3 are fixed. One of the methods of overcoming this difficulty is to shunt the variable resistor R_4 with a capacitance[5] C_4. With this symmetrical arrangement the power factor equation becomes:

$$\delta_x = \omega C_3 R_3 - \omega C_4 R_4$$

If this symmetrical bridge is operated at a one to one ratio the equation simplifies to:

$$\delta_x = \omega (C_3 - C_4) R_3$$

This, however, is not usually the case and the more complicated expression is the one generally used in calculating the power factor.

In the modified Schering bridge shown schematically in Fig. 2, the neutralization of the residual capacitance of capacitor C_3 is obtained by the introduction of a capacitor C_a which is connected between the mid

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[4] H. Schering, "Tätigkeitsbericht der Physikalische Technische Reichsanstalt," *Zeitschrift für Instrumentkunde*, Vol. 40, p. 124 (1920).
[5] E. Giebe and G. Zickner, "Verlustmessungen an Kondensatorem, " *Archiv für Elektrotechnik*, Vol. 11, pp. 109–129 (1922).

point of R_3 and the shields. This method of compensation makes it possible to operate the bridge as suggested by Schering and at the same time obtain the advantages of the symmetrical bridge.

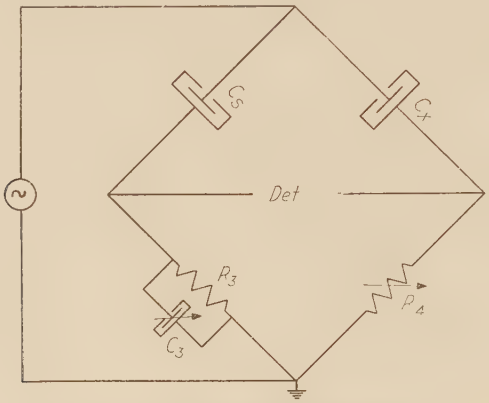

FIG. 1.—The Original Schering Bridge.

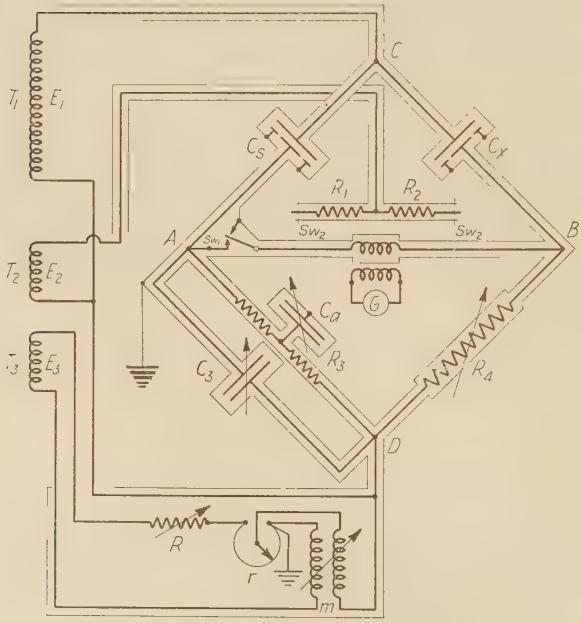

FIG. 2.—The Modified Schering Bridge.

In order to understand the operation of the bridge, consider Fig. 2 which shows two bridge circuits, one the Schering bridge and the other the auxiliary bridge. The completed bridge circuit shown in this figure is the

modified Schering bridge and consists of the standard air capacitor C_s, the specimen C_x, and the two lower bridge arms AD and BD. This bridge is supplied with power from a high-tension transformer T_1. In addition there is shown an auxiliary bridge consisting of two equal ratio arms R_1 and R_2 and the AD and BD arms. This auxiliary bridge is fed with power from the low-tension transformer T_2.

Either bridge may be set up by the use of the switches, Sw_2, indicated in Fig. 2. For example, when the auxiliary bridge connection is desired, the operation of the switches Sw_2 disconnects C_s and C_x from the A and B corners of the bridge and connects the resistance arms R_1 and R_2 in their respective places. When the switches are thrown to the opposite position, R_1 and R_2 are cut out of the circuit and the Schering bridge is established.

The bridge is completely shielded and guarded as indicated in Fig. 2. These shields and the guard rings of the standard air capacitor and of the specimen are usually all connected to ground. At balance the A and B corners of the bridge are usually at ground potential. This is accomplished by bringing the potential of the D corner of the bridge to slightly below ground by means of the shield balancing circuit, which consists of a coarse resistor R, a slide wire resistor, r, and a mutual inductor m, all fed by a low-potential transformer T_3. This arrangement not only avoids the necessity for a high-voltage circuit for establishing the shield potentials but assures that all parts of the bridge circuit with which the operator may come in contact are either solidly grounded or grounded through a low impedance circuit. It also assures that the guard rings of the standard and test capacitors are at the potential of the low-voltage or measuring electrodes by simply connecting them to the shielding system of the bridge.

A switch Sw_1 is used to connect one side of the detector to either the shields or to the A corner of the bridge. The other terminal of the detector is permanently connected to the B corner of the bridge.

The same power source supplies the primaries of all three transformers T_1, T_2, and T_3. The connections are arranged, however, so that only two of the transformers are excited at any one time. When the auxiliary bridge is used, transformers T_2 and T_3 are excited; and with the Schering bridge in circuit T_1 and T_3 are energized.

Operation:

The complete operation of the modified Schering bridge is as follows:

(*a*) The auxiliary bridge is established by throwing switches Sw_2 to the proper positions. The capacitor C_3 is set at its zero scale reading or some convenient value, C_o. Transformers T_2 and T_3 are energized and with the detector connected to the point A, the bridge is balanced by adjusting R_4 and the capacitor C_a, which compensates for the lead and the initial or residual capacitance in the C_3 arm.

(*b*) The detector is then connected to the shields by operating switch Sw_1 and the potential of the D corner of the bridge is varied by adjustment of the resistor R, the sliding contact of resistor r, and the setting of the mutual inductor m until the detector shows that the shield and the B corner of the bridge are at the same potential.

(*c*) Repeat (*a*) and then (*b*) until both the auxiliary bridge and the shield balances hold simultaneously.

(*d*) Switches Sw_2 are then operated so as to substitute the capacitors C_s and C_x for the resistors R_1 and R_2 respectively. Transformer T_2 is disconnected and transformers T_1 and T_3 are energized. With the detector connected to the A corner of the bridge, balance is obtained by varying R_4 and C_3, let C_3 be the new value of the capacitance.

(*e*) The detector is then connected to the shields and R, r, and m are adjusted for balance.

(*f*) Repeat alternately (*d*) and (*e*) until simultaneous balances hold. This completes the balancing operation.

Under these conditions, assuming all elements pure, the power factor of the specimen is given by the expression:

$$\delta_x = \omega \Delta C_3 R_3 \qquad (1)$$

Here ΔC_3 represents the change in the capacitance of capacitor C_3 from its setting C_o in the auxiliary bridge to the setting C_3 required to balance the bridge with the specimen in the circuit.

The capacitance, C_x, of the specimen is given by the relation:

$$C_x = C_s \frac{R_3}{R_4'} \qquad (2)$$

Tests:

The bridge circuits were set up and tests were made to determine the characteristics of the bridge and the correctness of the theoretical calculations. In this work the detector used was the pointer galvanometer with amplifier. The sensitivity of the bridge with the detector available and at the voltages used was 0.00003 in power factor. The voltage supplied to the modified Schering bridge by transformer T_1 was 700 v. The voltage for the auxiliary bridge amounted to 5 v. The transformer T_3 gave 2.5 v. The source of power used in the work consisted of a 5 kva., 3 phase, 60 cycle pure sine wave generator.

EXPERIMENTAL RESULTS

1. *Guard—Bridge Corner Capacitance:*

An analysis of the bridge showed that the balance relation, Eq. 1, was free from the effect of capacitance between the shields and the A and B bridge corners. To verify this the following tests were made:

(*a*) The auxiliary bridge was first carefully balanced. A variable air capacitor having a range from 200 to 4200 $\mu\mu$f. was then placed in turn between the shields and the A and B corners of the bridge. This inserted capacitor was varied over its entire range without disturbing the balance.

(*b*) The same tests were repeated in the Schering bridge and gave the same result.

2. *Balance Equations All Elements Pure:*

(*a*) The two important relations for the auxiliary bridge are:

$$R_1R_4 = R_2R_3 \quad (3)$$

and

$$C_0 = \frac{C_a}{4} \quad (4)$$

The resistors used for R_1, R_2, and R_3 were nominally 10,000 ohms. In numerous balances over a period of more than a month the value of R_4 necessary for balance ranged between 9999 and 10,000.6 ohms. It is apparent, therefore, that the relation holds at least to one part in ten thousand. The variation in R_4 that was obtained may be attributed to such factors as changes in temperature, contact resistances, sensitivity, and to the personal element.

To check the relation $C_a = 4\ C_0$, both air and mica capacitors were used with the following results:

For $E_2 = 5$ v., C_3 and C_a precision air capacitors:

C_3	C_a	$C_a/4$
375 $\mu\mu$f.	1484 $\mu\mu$f.	371 $\mu\mu$f.
342 $\mu\mu$f.	1352 $\mu\mu$f.	338 $\mu\mu$f.
295 $\mu\mu$f.	1190 $\mu\mu$f.	297 $\mu\mu$f.

For $E_2 = 2$ volts, C_3 and C_a mica capacitors:

C_3	C_a	$C_a/4$
0.05 $\mu\mu$f.	0.20 $\mu\mu$f.	0.050 $\mu\mu$f.
0.05 $\mu\mu$f.	0.20 $\mu\mu$f.	0.050 $\mu\mu$f.

In these tests the capacitance of the leads was neglected. The results check Eq. 4.

(*b*) The correctness of bridge Eq. 2 was checked with the bridge operated at 400 v. and with precision type air capacitors forming both the C_s and C_x arms. During the test, C_s was held constant at 586 $\mu\mu$f. and C_x was varied. The results are given below:

R_3	R_4'	C_x	$\frac{C_xR_4'}{R_3}$	C_s
10 000 ohms	8 310 ohms	708 $\mu\mu$f.	588 $\mu\mu$f.	586 $\mu\mu$f.
10 000 ohms	10 020 ohms	587 $\mu\mu$f.	588 $\mu\mu$f.	586 $\mu\mu$f.
10 000 ohms	12 630 ohms	465 $\mu\mu$f.	587 $\mu\mu$f.	586 $\mu\mu$f.
10 000 ohms	17 090 ohms	343 $\mu\mu$f.	586 $\mu\mu$f.	586 $\mu\mu$f.

A comparison of the results in the last two columns shows clearly the correctness of the equation.

(*c*) The correctness of the power factor Eq. 1 was checked against the Low Power Factor Standard[1] of Kouwenhoven and Berberich. The standard capacitor consisted of a highly polished and cleaned flat brass plate air capacitor provided with guards. The measurements were made at 700 v. with the results given below. In every case they check to within the sensitivity of the bridge as used:

Standard of Power Factor	Measured Power Factor	Apparent Error
0.000000	0.000*000*	0.000*000*
0.000195	0.000*215*	0.000*020*
0.000996	0.001*025*	0.000*029*
0.001993	0.001*999*	0.000*006*

(*d*) The power factor Eq. 1 for the bridge is independent of the value of the variable resistance arm, R_4. To verify this a series of measurements of the Power Factor Standard was made at different bridge ratios. The results are given below for two sets of measurements. The results show that the measured values of power factor are independent of the ratio of C_s to C_x at least to within the sensitivity of the bridge and detector.

				Power Factor Standard	
R_3, ohms	R_4, ohms	C_0, $\mu\mu$f.	C_3, $\mu\mu$f.	Measured δ_x	Rated Value δ_x
10 000	5 005.8	223	223	0.00000	0.000000
10 000	9 983.0	223	223	0.00000	0.000000
10 000	10 954.0	223	223	0.00000	0.000000
10 000	5 005.8	223	747	0.001*978*	0.001993
10 000	9 983.0	223	750	0.001*987*	0.001993
10 000	10 954.0	223	749	0.001*983*	0.001993

(*e*) An investigation was made to determine the effect of the use of a capacitor in the C_a arm having an appreciable phase defect angle. In order to simulate this condition the variable air capacitor, C_a, which meggered infinity, was shunted by grid leaks of various values. When a five megohm grid leak was connected across C_a it produced a change of six parts in 10,000 in R_4. It is evident, therefore, that C_a should be a good air capacitor with high insulation resistance.

(*f*) A phase defect in R_3, since it will be of the nature of a capacitance, is compensated for by an increase in C_a. This is substantiated by the results given below for two separate measurements of the same specimen using different values of C_0:

C_0 = 50 $\mu\mu$f.	C_3 = 581 $\mu\mu$f.	P.F. = 0.001*992*
C_0 = 223 $\mu\mu$f.	C_3 = 750 $\mu\mu$f.	P.F. = 0.001*987*

One will note that the power factor obtained in both cases was the same to within the sensitivity of the bridge.

[1] W. B. Kouwenhoven and L. J. Berberich, "A Standard of Low Power Factor," *Transactions*, Am. Inst. Electrical Engrs., Vol. 52, June, 1933, p. 521.

Conclusions

1. The modified Schering bridge presented in this paper had a sensitivity of 0.00003 for power factor when operated at 700 v. and 60 cycles with the available detector. This sensitivity should not by any means be considered the limiting one for this bridge since it may be improved by the use of either a higher voltage or a more sensitive detector.

2. The over-all sensitivity is limited by the less sensitive of the two bridges, either the auxiliary or the Schering. For this reason the voltage applied to the auxiliary bridge should be sufficiently high to give at least the same sensitivity to changes in the C_3 arm that exists in the Schering bridge.

3. The balance equations are shown to be correct at least to within the sensitivity employed.

4. The low impedance low-voltage shield balancing arrangement adds considerably to the safety of operation of this bridge compared to other Schering bridges employing the Wagner ground with its adjustable high-voltage element.

5. The guard rings of the standard and specimen need not be balanced separately but are brought to the proper potential by simply connecting them to the shields.

6. The method of compensating for the minimum or residual capacitance not only affords compensation at all ratios but also simplifies the calculations considerably.

7. No adjustable high voltage standard is required in this bridge.

8. The operation of the bridge is relatively simple and the shield balancing circuit is quite stable. Once properly made the auxiliary balance needs to be checked only occasionally.